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EVALUATING CHANGES IN THE HEALTH CARE DELIVERY SYSTEM: AN APPLICATION TO INTENSIVE CARE MONITORING

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ABSTRACT

This paper proposes a tool for evaluation of potential changes in the system for the delivery of health care. Starting with a definition of a community health production function, the paper introduces the concept of "nested production functions" in health care. The production function approach is seen as providing a mechanism for explicit consideration of the substitution and optimal input combination questions which are the basis of all evaluations of changes in the health care delivery system.

The discussion of this technique is followed by an application to intensive care monitoring. While actual data has not been gathered, we formulate a model for evaluating the effect of computerization of certain intensive care monitoring procedures.

I. THE PRODUCTION OF HEALTH IN THE COMMUNITY

The system of delivering health care may be viewed as the employment of inputs, such as doctors, nurses, outpatient clinics, hospitals, population nutritional levels, environmental quality, and other factors, producing an output - the "level of health."

There is much controversy in the economics and public health literature about the proper measure of "level of health."* Some of the commonly used definitions of this measure are the percentage of people sick at any time, the average number of days lost to illness, the expected earnings stream of the population of a suitably defined community and so on.

Regardless of the measure of output, one might imagine a "community health" function that expresses the "level of health" output in terms of the levels of the inputs, such as number of doctors, number of hospitals, etc. Such a function is referred to by the economist as a production function and by the engineer as a transfer function. We shall employ the former term.

Intuitively, we should expect our "community health" production function to have several obvious properties:

- An increase in the level of any input should not produce a decrease in the level of output. If we increase the number of hospitals in a community, we expect community health to increase, measured by any standard.

*See for example, Avedis Donabedian, "Evaluating the Quality of Medical Care," in Health Services Research, edited by Donald Mainland, (Milbank Memorial Fund, 1967), pp. 166-203, and A. H. Packer, "Applying Cost-Effectiveness Concepts to the Community Health System," Operations Research, Volume 15, (1967), pp. 227-253.

• Subsequent increases in the level of any one input, all other inputs being held at a constant level, should produce ever smaller absolute increases in the level of output. The reason is that inputs may complement one another. For example, the marginal benefit from adding an additional hospital while holding the number of doctors constant - and thus, in effect, spreading them thinner - will decrease for each hospital added.

• The marginal increase in output resulting from an increase in any one input will be greater if other inputs are also increased. This also results from the complementarity property; i.e., increases in the number of hospitals will have a greater effect if the number of doctors is increased at the same time.

• Many different combinations of inputs can produce the same level of output. In some sense, inputs to community health are substitutes for each other; that is, a given level of health might be produced by alternative combinations of nurses and doctors, doctors and clinics, etc.

This property is represented in figure 1. The curves in figure 1 show the alternative combinations of two inputs (doctors and nurses) that produce a given level of output (average number of days lost to illness). The output of 10 days per year lost to illness may be achieved with D_1 doctors and N_1 nurses, or D_2 doctors and N_2 nurses. If the level of one input is increased - for example, if the number of doctors increases to D_3 and the other is held constant - the level of output reaches a more desirable level - in this case, to 8 days per year lost because of illness. Implicit in the concept of substitutability is the fact that nurses may be excellent substitutes for doctors in some

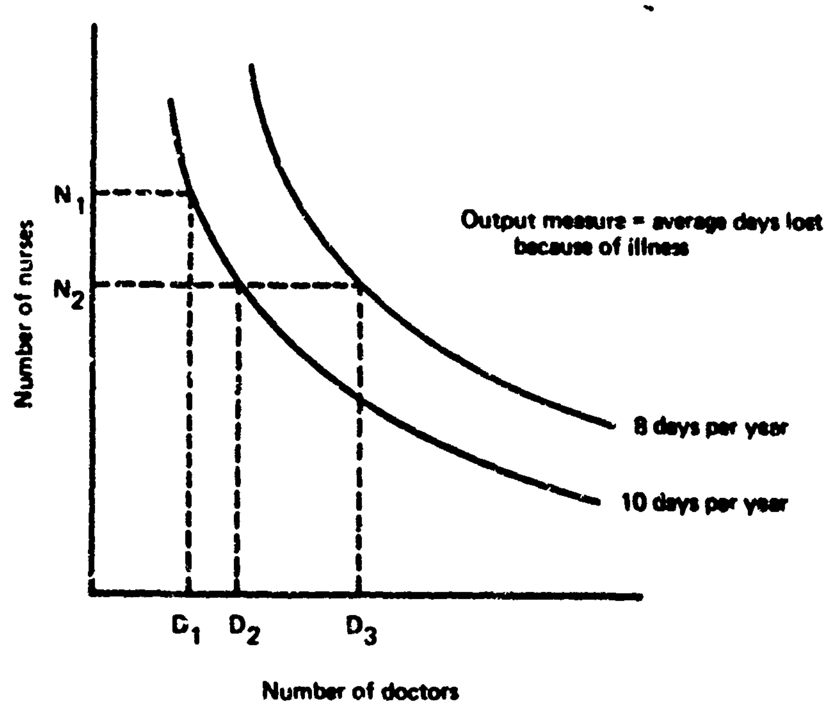

FIG. 1: A HYPOTHETICAL SUBSTITUTION CURVE BETWEEN TWO INPUTS TO COMMUNITY HEALTH

functions - as the taking of blood pressure and the administration of injections - but poor substitutes in other functions, such as surgical procedures. This trivial example illustrates the substitutability that characterizes production functions.

One final concept that must be introduced is a budget function. This function relates the unit price and quantity of each input to the appropriate budget level. Assume that the community has a fixed budget to use for maintaining a level of health in the community. In theory, the community will seek to maximize its level of health by allocating the fixed budget optimally among the different categories of resource inputs.

To carry forward our two-resource example, let P_D and P_N represent the unit prices of doctors and nurses respectively. If our budget is an amount C and if these are the only two inputs in our community health production function, the quantities of doctors D and nurses N are constrained as follows:

$$P_D \cdot D + P_N \cdot N \leq C \ .$$

Figure 2 shows that when the budget constraint is imposed on the curves of equal-health levels (measured, in this case, in average days lost per year), the highest level of output occurs at the point of tangency of the highest output curve (the curve farthest to the right) with the budget constraint. This result is clear from an examination of point A, which satisfies the budget constraint but represents a lower level of output than point B, the point of tangency. Any point on a higher output curve, such as E, cannot be attained with budget C. Thus, the optimal

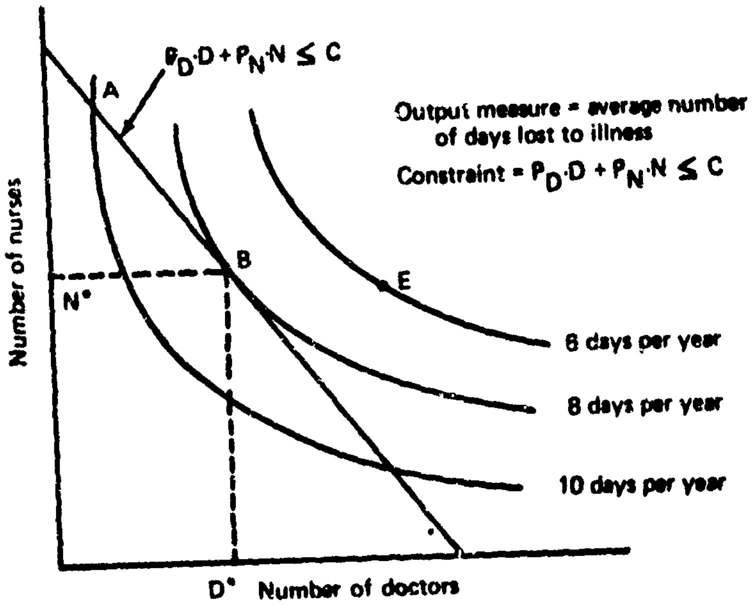

FIG. 2: DETERMINATION OF OPTIMUM MIX OF INPUT RESOURCES WITH BUDGET CONSTRAINT

solution is to allocate the budget so that D^* doctors and N^* nurses are available; the resulting level of health is expected to be an average of 8 days per year lost to illness.

Use of the production function model involves a 2-stage procedure In the first stage, the production function is estimated with the use of historical data. The estimated function is then assumed to describe the process for at least the immediate future; in the second stage, as we have seen, it serves as an input to the model.

The production function concept offers three major advantages in an economic analysis:

- Determination of the substitution and complementarity properties of the inputs to a production process: Production functions enable one, in the context of community health care, to determine how the various inputs substitute for each other (nurses for doctors, paramedical people for nurses, and so on) and complement one another (doctors working in hospitals, nurses working for doctors, etc.) in the production of any level of output.

- Determination of the optimum combination of categories of input resources under a given constraint: When combined with a budget constraint, the production function permits determination of the input resource mix that yields the greatest output for a given cost constraint, or, alternatively, the lowest cost at which a given output can be achieved.

- Determination of the returns to scale, or the multiplicative effect on output measure caused by proportionate changes in the levels of inputs.

These are exactly the types of questions raised when changes to the health care delivery system are proposed. Potential changes can always be viewed as changes in the levels of one or more of the input resources (suitably defined).

There have been many examples of the successful application of production function models to problems in industry and government.* In a recent article, several authors made a significant attempt to estimate a production function of community health, much as is described above.**

II. "NESTED" PRODUCTION FUNCTIONS

One of the inputs in a production function of the health of a community is the hospital. Figure 3 shows that the hospital itself is a complex system that converts such inputs as out-patient clinics, in-patient wards, research facilities, into such outputs as number of patients treated, morbidity and mortality of patients treated, and doctor, nurse, and patient satisfaction.

Theoretically, one could develop a function that relates the inputs of the hospital to its outputs along any of these measures in exactly the same way as, previously, we related inputs of community health to measures of output. The output of the "hospital production function" is just one of the inputs to the community health production function.***

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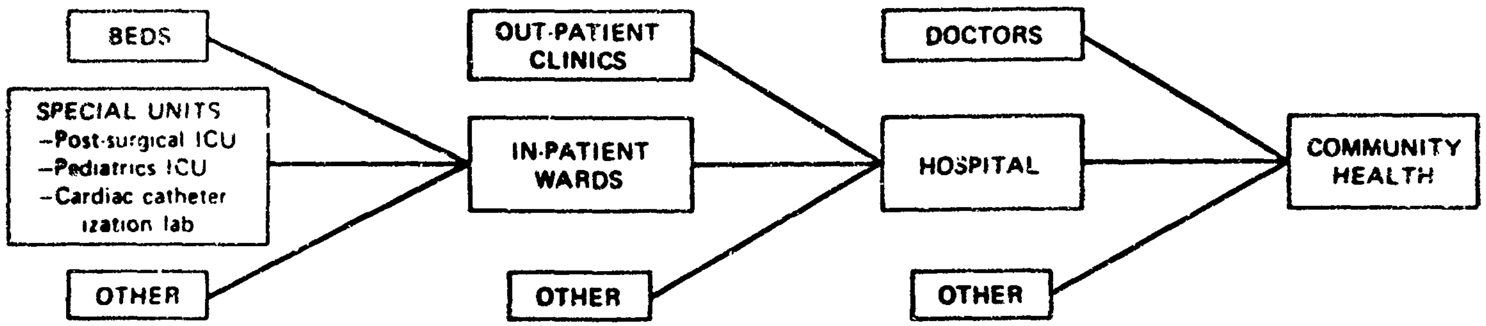
* For an extensive treatment of the theory and applications of production functions, see A. A. Walters, "Production and Cost Functions: An Econometric Survey," Econometrica, Volume 31, Nos. 1-2 (Jan.-April 1963), pp. 1-66 or The Theory and Empirical Analysis of Production, edited by Murray Brown, (Columbia University Press, New York, 1967).
**Richard Auster, Irving Levesan, Deborah Sarachek, "The Production of Health, An Exploratory Study," The Journal of Human Resources, IV, 4, (Fall, 1969), pp. 411-436.
***The most extensive work in the estimation of hospital production is contained in Martin S. Feldstein, Economic Analysis for Health Service Efficiency, (North-Holland Publishing Co., Amsterdam, 1967.)



Appropriate production function	Special care units	In-patient care	Hospital	Community health
Potential output measures	Morbidity and mortality of patients in special units Time expended by doctors, nurses, patients in delivery of care Reproducibility of data	Morbidity and mortality of in-patients Doctor, nurse patient satisfaction	Number of patients treated Morbidity and mortality of patients treated Doctor, nurse, patient satisfaction Research output Students taught	Average days lost Probability of illness Expected lifetime earnings
Inputs	Doctors Nurses Beds Machinery (computerized and others) Technicians Medications and supplies	Beds Screening facilities Doctors Nurses Special-care units Medications and supplies	In-patient wards Out-patient clinics Research facilities Teaching facilities	Clinics Doctors Nurses Hospitals Nutrition Health education

FIG. 5: EXAMPLE OF "NESTING" OF PRODUCTION IN HEALTH CARE DELIVERY SYSTEM

Similarly, we could develop functions for any of the inputs to community health, such as an effectiveness measure for neighborhood health centers or outpatient facilities.* Such a measure would itself be an output related to its component inputs. (The production of certain inputs to community health, such as level of air pollution or quality of the water would be beyond explicit consideration in the health care delivery system.)

Extending our previous discussion of the hospital, figure 3 shows that hospital in-patient care is a function of many inputs, including numbers and types of beds, screening procedures, drugs, doctors, and nurses. (Doctors and nurses may appear as inputs in several of the stages of our system; we can differentiate among doctor hours spent in a hospital, in an intensive care ward, or in the doctor's own office, and we can do the same for nurses.)

Among the inputs to in-patient care are the special units that the hospital has available for specific types of patients. Each of these special units may further be viewed in terms of a function that relates inputs of doctors, nurses, technicians, and machines to outputs that depend on the type of special unit under consideration. The output of the special unit production function is an input to the in-patient production function. This "nested" model provides an excellent structure for the study of problems related to the system for the delivery of health care. Once the appropriate functions are estimated, this model considers the total effects that changes in any of the inputs at any stage in the system would have on the entire system of health care delivery.

*A recent effort along these lines is Joel W. Kovner, "A Production Function for Outpatient Medical Facilities," University of California, Los Angeles, California, 1968.

Suppose one were evaluating the implementation of a system for the computerized monitoring of intensive care patients. (This is the example evaluation discussed in Section IV.) If the parameters of the appropriate special-unit production functions are known or can be estimated by an econometric technique, one can show how this increase in one factor (monitoring equipment) influences the level of output that can be achieved in the special unit. The estimation would also isolate the substitution effects on the other inputs (such as nurses and technicians) for a given level of output. Finally, given the costs of each of the inputs, one can determine whether this expenditure for machinery is optimal (relative to some measure of output for the unit) when compared with other uses for funds within the unit.

As noted previously, the outputs for these special units are inputs for the in-patient production function, which is, in turn, an input to the hospital production function and ultimately to the community production function. If the parameters of each of these functions are known, it is an easy matter to measure the effect of an increase in the machinery input in one (or more) special units on the in-patient population, the hospital, and the community.* It is this effect on some measure of community health that one would, ideally, like to isolate in evaluating changes in the health care delivery system.

III. PROBLEMS IN IMPLEMENTATION

Sections I and II have proposed a framework for the evaluation of changes in the system for the delivery of health care. Before providing

*Some assumptions about the marginal rates of substitution among inputs at each stage are necessary to do this.

a specific example of how this methodology may be used, two potential problem areas should be cited:

A. Post Hoc evaluation: Production function estimation can only be performed on actual data. If the potential change in the health care system which is being evaluated involves a new technology, a production function can only be estimated after the technology is implemented. For many types of evaluation, such as whether a community should spend health dollars on hospitals or combating air pollution, this does not present a problem. However, the evaluation of a new machine to monitor intensive care patients can only be performed on a post hoc basis.

B. Defining and quantifying measures of outputs and inputs: A major topic in recent health care research has been the definition of output measures for various stages in the health care system. This issue must be faced in any evaluation and is not a problem unique to our methodology. The advantage of the production function technique is that once these inputs and outputs are specified and quantified, the interrelationships can be clearly established.

IV. AN APPLICATION TO INTENSIVE CARE MONITORING

A. Introduction.

To provide further understanding of the methodology proposed in this paper, an application to intensive care monitoring is discussed. By its very nature, an intensive care facility is designed for close surveillance of patients with conditions which are potentially correctable if discovered shortly after they occur. In most such facilities the nurse/patient ratio is much higher than elsewhere in the hospital. Inevitably, it was suggested that computers could perform this monitoring and the associated bookkeeping operations more efficiently than nurses, and systems for this purpose have been developed and implemented. However, their high cost requires justification in terms of efficiency. Assuming that the computerized system is to be implemented at one (or more) test facilities, we will determine whether computerized monitoring is a desirable expenditure for the intensive care unit from a cost-benefit point of view.

B. Measures of Output.

Morbidity and mortality are the commonly accepted measures of effectiveness for an intensive care ward. We will use length of stay for patients who live to leave the ward, and the mortality rate as two measures of output for the ICU.

C. Patient Stratification.

Since we cannot expect true random samples of patients in the unit(s) which might be studied, the above measures of output will be meaningful only when we have corrected for differences in these measures that might occur as a result of possible changes in the types of patients treated with and without computerized monitoring. It is also desirable to correct for patient differences, since different groups might derive quite different benefits from the system. This information could be quite important to a hospital that is considering adoption of the automated system, especially if its case mix is very different from the mix of the test hospital(s).

Patient stratification will usually take place on the basis of the patient's primary diagnosis (or primary surgical procedure). The standard codes for this purpose, such as the International Classification of Diseases, Adapted (ICDA), are in the "digit level" format. We can therefore be as fine in our stratification as the data allows us to be. In the ICDA classification system, for example, 29.1 is the code for a pericardictomy, and 29 signifies an operation on heart or pericardium. The extent of our stratification will depend on the number of patients in a category at each code level. We can thus estimate two production functions (one for length of stay, one for mortality) for each patient class as defined above.

D. Inputs to the Production Function.

The inputs to the ICU production can be treated in two categories, those related directly to the resources of the ICU and those not related to these resources. In the latter category, we include those variables affecting a patient's length of stay or probability of survival that are characteristics of the patient or of the hospital but not of the ICU.

1. Variables not related to the ICU.

Examples of these variables are:

a. Age

b. Sex

c. Entering severity: One could correct for a patient's entering severity by establishing an index on a scale from 1 to 10, to represent the relative severity of patients within a given patient class. (That is, we could say that a patient with severity 8 is more critical than another in the same class with a severity index of 3, but we could not compare this patient with one of another class with an index of 8.) A numerical scoring system could be constructed to take data that is readily available and produce a value on our relative index.

The inputs to such a scoring system would clearly differ for different types of ICU's, and may include information available from the patient's record such as preexisting medical complications, number of MD's on operating team and length of time under anesthesia or else the more subjective evaluation of the patient's doctor.

d. Stress on the ICU: The hospital will put stress on the unit in terms of the demand for beds in the unit. This might have an effect on the length of time a patient is kept in intensive care. It is therefore necessary to develop a measure of external stress based on such indicators as the ratio of ICU length of stay to hospital length of stay, changes in the distribution of the severity dimension of a given patient class, and average waiting time in the queue for the surgical rooms that supply the ICU population (if this is the case).

Since we are attempting to isolate the interactions of the various resource inputs to health care in the ICU, we must first correct for variation in our output measures caused by factors not related to the ICU. We can correct for age, sex, entering severity and stress and determine the remaining variation which may be attributable solely to the ICU related resources.

2. Variables related to the ICU.

The second category of inputs consists of those which are related to the resources of the ICU and have a functional relationship with our two output measures.

Some of the variables in this category are:

a. Nurses: One could measure the number of nurse hours allocated to each patient in the unit. Nurses would be differentiated among the categories of nursing personnel such as registered nurses, practical nurses, orderlies, and technicians.

Practical limitations on data gathering might prevent the determination of actual nurse hours spent on each patient. However, an allocation procedure can be established to ration the available number of nurse hours to patients in the ward on any one shift.* The sum of the hours allocated to patient i over all shifts during which he is in the ICU will represent the value of this input associated with his treatment. This type of allocation procedure could be used for each category of nursing personnel.

b. Doctors: We can consider doctor-hours in terms of at least three categories: specialists, residents, and family doctor. To the extent that doctor visits are recorded on a patient's record, we could use these times as the input. For doctors on duty in the unit, we can use a proportional allocation scheme similar to that described for the nursing personnel.

c. Type of monitoring: A patient may experience three types of monitoring: by a computerized facility, in the routine manner in a unit where some of the beds are computer-monitored, or in the routine manner in a totally non-computerized ward. We distinguish between the latter two types of monitoring because it seems reasonable to anticipate spillover effects for patients in a computerized ward, even if these

*One simple allocation procedure would assume that the nurse's time is allocated equally among all patients in the unit. A more sophisticated allocation procedure would weight the time spent with a patient by his severity relative to other patients in the unit.

patients are not monitored by the computer.* By distinguishing beds in a computerized ward which are routinely monitored from beds which are truly routinely monitored, we hope to measure the size of this spillover effect.

E. Estimation of the ICU Production Function.

The production functions for the variation in our output measures after correction for the non-ICU related variables are estimated with the ICU input variables defined above. Two production functions are estimated for each patient class. Data should be gathered from the test hospital implementing the system as well as from a comparable hospital which monitors patients in the routine manner. If the data inputs described above can be taken from historical records, a time series can be used for the test hospital only. However, it is likely that the necessary data can be generated only after implementation, thus requiring a combined cross-section and time series analysis.

F. Optimal Inputs in the Intensive-Care Unit.

We now wish to determine whether the increase in the total dollar resources of the ICU represented by incorporation of a computerized monitoring facility is optimal. Given that we observe a set of benefits that represents a shift to a higher level of production, and in so doing experience an increase in costs, we wish to determine whether the same level of output can be achieved at a lower cost, or whether for the same cost incurred we could achieve an even higher level of output.

The results of the production function model will give us the optimal combination of inputs to achieve given levels of two measures of output for each patient class. With our model, any hospital (including

*For example, the presence of a technician may reduce the failure rate of conventional electronic devices in the unit.

our test hospitals) can take its historical case mix of patient classes and observed values of "non-care" variables (age, sex, severity, stress) within each patient class and, by taking weighted averages of the estimated production function results, determine a true average length of study and survival probability for an ICU patient. Thus, by isolating the true effects of the ICU resources on these benefits, our model is general enough for use by any hospital. These aggregated measures are used for the remainder of this section.

The results we could display for a hospital appear in figure 4. The first row of each table contains the output and input measures of the current ("before") ICU operations and the associated cost of running the "before" ICU. (Of course, the inputs could be stratified into finer categories than those indicated here.) The second row of each table shows the results that will be observed after the computer is introduced. Presumably, our output in each case will improve, costs will rise, and the numbers of nurse and doctor inputs may change. The last two rows of each table represent the results of the production function model.

The third row identifies a different configuration of the machinery input - that is, the ratio of computerized beds to non-computerized beds - which, when combined with specified levels of the other inputs, will yield a higher output (L_3 or PR_3) for the same cost. It will also be possible to determine how the same level of output, displayed in the second row, can be achieved for other levels of the inputs at lower than the "after" costs. This is shown in the last row of each table in figure 4.

This approach would seem to give the optimal size of a computerized monitoring system, but we shall not observe a system intermediate to the "before" and "after" ICU's in each hospital and shall therefore be unable to identify the optimal size of a monitoring system. Rather, we shall be able to determine the configuration of the unit - that is, the percentage of each type of bed (either computerized or not) that should be in the ICU of each hospital.

The production function methodology has thus provided a tool for an economic evaluation of this change in the health care delivery system.

OUTPUTS Average length of stay	INPUTS			COST
	Nurses	Doctors	Machines*	
L_1	N_1	D_1	"Before" configuration	$C_{\text{"Before"}}$
L_2 ($<L_1$)	N_2	D_2	"After" configuration	$C_{\text{"After"}}$
L_3 ($<L_2$)	N_3	D_3	Different configuration	$C_{\text{"After"}}$
L_2	N_4	D_4	Different configuration	$C_{\text{Different}}$ ($<$"After")

OUTPUT Mortality rate	INPUTS			COSTS
	Nurses	Doctors	Machines*	
PR_1	N_1	D_1	"Before" configuration	$C_{\text{"Before"}}$
PR_2 ($<PR_1$)	N_2	D_2	"After" configuration	$C_{\text{"After"}}$
PR_3 ($<PR_2$)	N_3	D_3	Different configuration	$C_{\text{"After"}}$
PR_2	N_4	D_4	Different configuration	$C_{\text{Different}}$ ($<$"After")

*Ratio of computerized beds to non-computerized beds.

FIG. 4: PROPOSED DISPLAY OF ANALYSES OF ICU PRODUCTION FUNCTIONS

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